# Effect of irradiation temperature on degradation of REBCO tapes

David Fischer*, Alexis Devitre, Kevin Woller, Zoe Fisher, Zach Hartwig

*Plasma Science and Fusion Center, Massachusetts Institute of Technology*

*dafisch@mit.edu

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# Acknowledgements

- Discussions with TU Wien
  - Michael Eisterer
  - Raphael Unterrainer
- Provided REBCO samples
  - Bridged AMSC samples: Nick Strickland *et al* (Victoria University of Wellington)
  - Faraday Factory Japan
- Eni
- Commonwealth Fusion Systems

# Outline of presentation

- Motivation for this research
- Replication of fusion environment
- Cryogenic ion irradiation facility at MIT
- Experimental results
  - Cryogenic vs warm irradiation
  - Degradation mechanism?
  - Annealing recovery
- Next steps
- Conclusions

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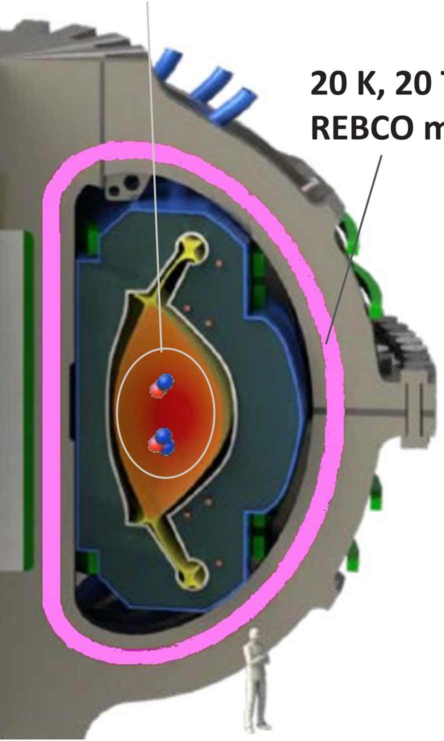
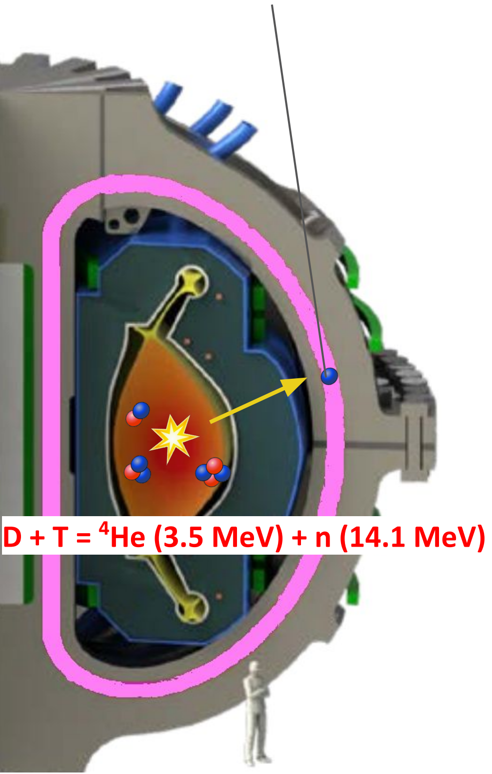
# REBCO must survive radiation damage in fusion devices



**> 100,000,000 K**
**deuterium-tritium plasma**

**20 K, 20 T**
**REBCO magnet**

# REBCO must survive radiation damage in fusion devices



**High energy neutrons reach magnet**

**D + T = $^4$He (3.5 MeV) + n (14.1 MeV)**

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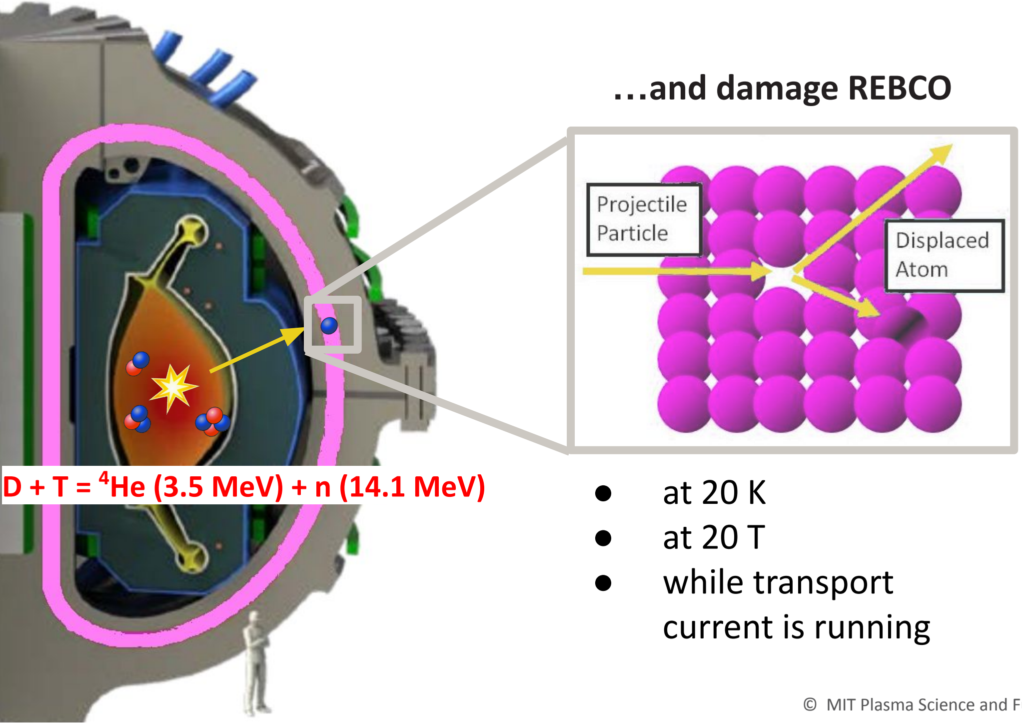

**…and damage REBCO**

**D + T = $^4$He (3.5 MeV) + n (14.1 MeV)**

- at 20 K
- at 20 T
- while transport current is running

# REBCO must survive radiation damage in fusion devices

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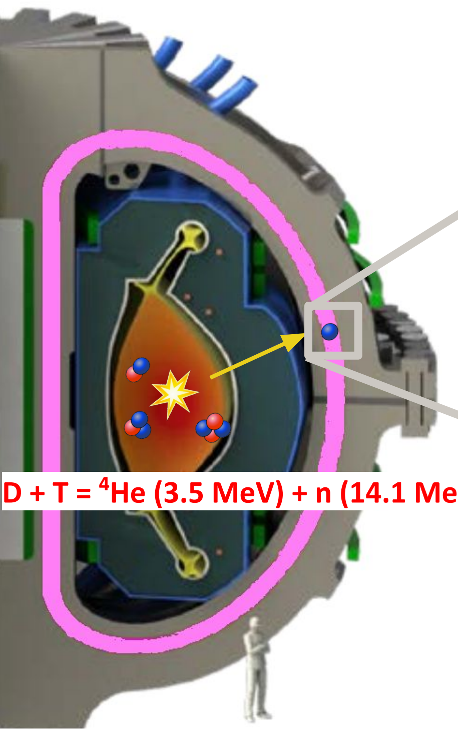

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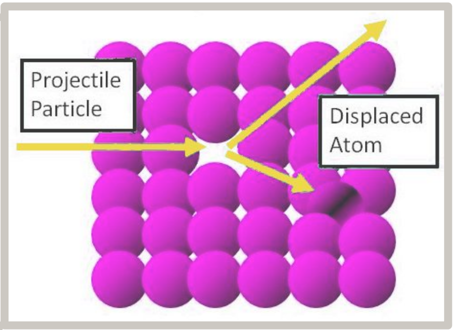

- at 20 K
- at 20 T
- while transport current is running

**…which limits the life of a fusion power plant**

by eventually decreasing:

- critical currents: ↧ $I_{op} < I_c$
- achievable field: ↧ $B \propto I_{op}$
- power output: ↧↧↧↧ $P \propto B^4$

Magnet system is most expensive (>>$100M) part of fusion device and a lifetime component

Degradation behaviour has to be understood to develop long-lasting and economically viable fusion power plants!

# REBCO must survive radiation damage in fusion devices

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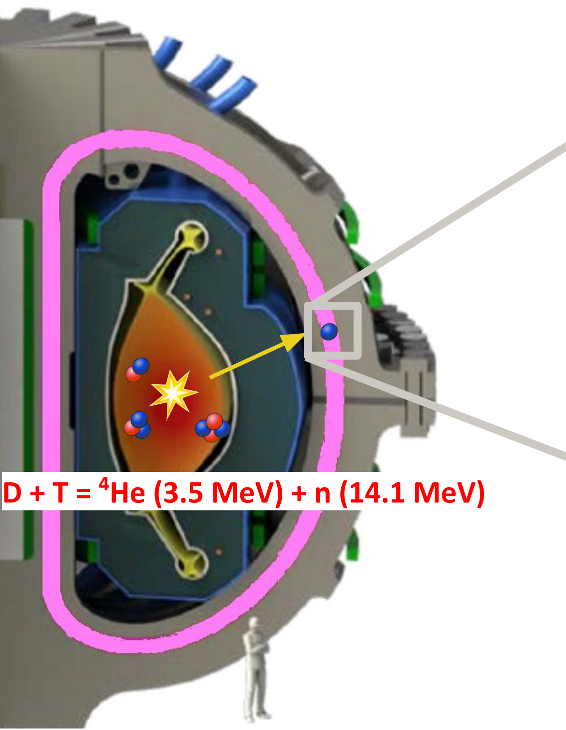

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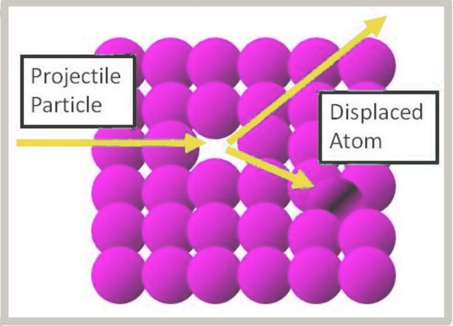

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Magnet system is most expensive (>>$100M) part of fusion device and a lifetime component

Degradation behaviour has to be understood to develop long-lasting and economically viable fusion power plants!

**A test facility that replicates the fusion environment is needed!**

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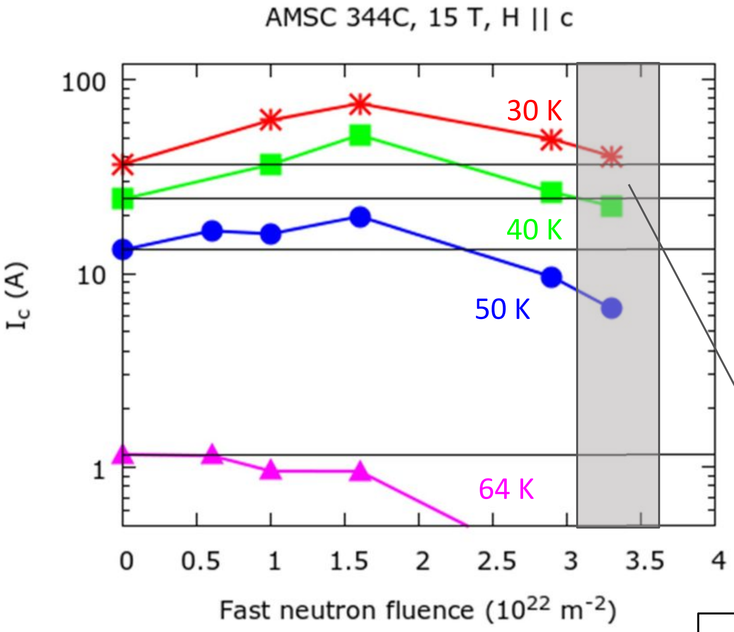
# The ideal test environment matches fusion conditions

## How to create fusion-like environment for REBCO tapes ?

| Priority | Ingredients to emulate fusion environment | What is most fusion-like? |
|---|---|---|
| 1 | Irradiation temperature | Fusion magnets operated at ~20 K |
| 2 | Annealing effects prevented | In-situ analysis without warm-up |
| 3 | High magnetic field | Field on fusion magnets >20 T |
| 4 | Irradiation type | Neutrons with relevant energy spectrum |
| 5 | $I_c$ anisotropy assessment | REBCO tapes experience all field angles |
| 6 | Performance assessment | Transport current measurement |

# High fluence neutron irradiation hints at radiation limits

**REBCO tapes after neutron irradiation at 330 K**



Fluence region where degradation starts for $I_c$ at low temperatures

D. X. Fischer, *SUST*, 31 (2018) 044006.

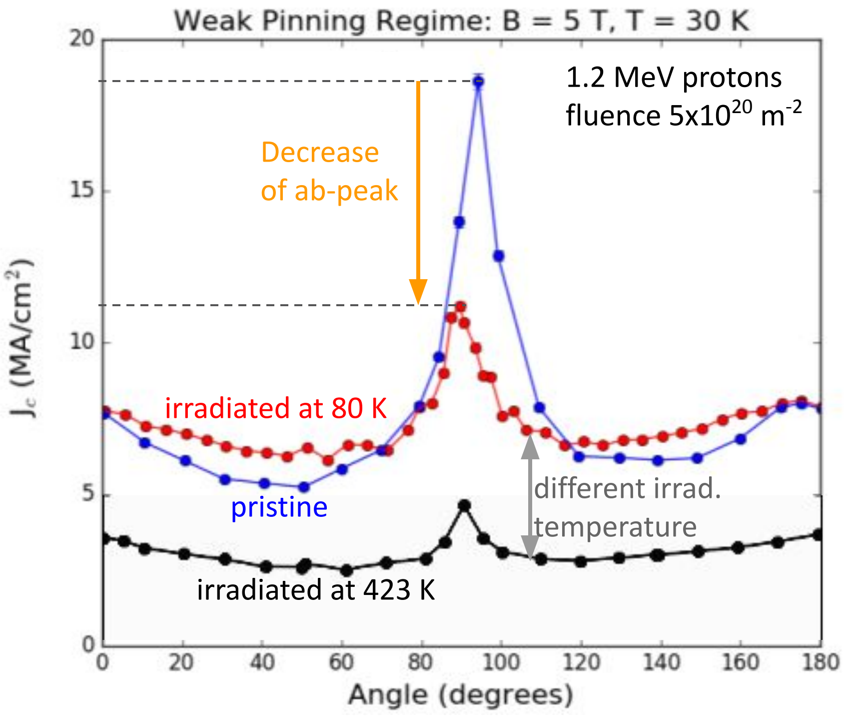
**Checklist for fusion-like conditions**

| | |
|---|---|
| ☹ | irradiation temperature |
| ☹ | annealing effects prevented |
| ☺ | high magnetic background field |
| ☺ | irradiation type |
| ☹ | $I_c$ anisotropy assessment |
| ☺ | transport current measurements |

In-core irradiation of REBCO tapes provides a first estimate for the radiation resistance, even if not conducted at cryogenic temperatures.

# Temperature during irradiation influences degradation

**REBCO tapes after proton irradiation at 80 K**



1.2 MeV protons
fluence $5\text{x}10^{20}$ m$^{-2}$

Decrease
of ab-peak

irradiated at 80 K

pristine

different irrad.
temperature

irradiated at 423 K

B. N. Sorbom, MIT PhD Thesis, 2017.

**Checklist for fusion-like conditions**

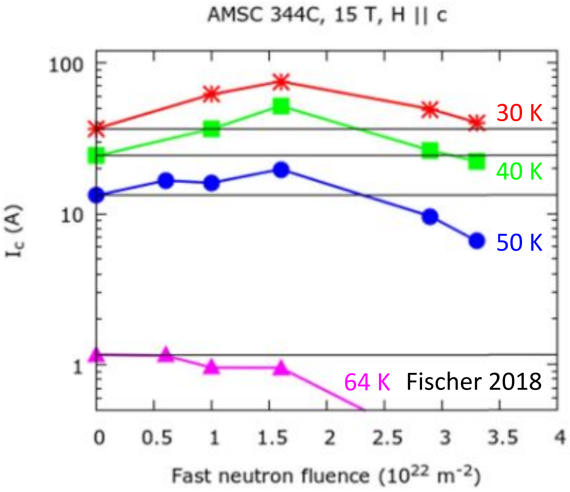
| | |
|---|---|
| 😐 | irradiation temperature |
| ☹ | annealing effects prevented |
| 😐 | high magnetic background field |
| 😐 | irradiation type |
| ☺ | $I_c$ anisotropy assessment |
| ☺ | transport current measurements |

Cold irradiated REBCO tapes were warmed-up and then measured in external facility - annealing occurred. Takeaways:

1. irradiation temperature matters
2. $I_c$ anisotropy decreases after irradiation

# Previously missing: cold irradiation with in-situ analysis

Neutron irradiation at 330 K



| | | |
|---|---|---|
| ☹ | irradiation temperature | 😐 |
| ☹ | annealing effects prevented | ☹ |
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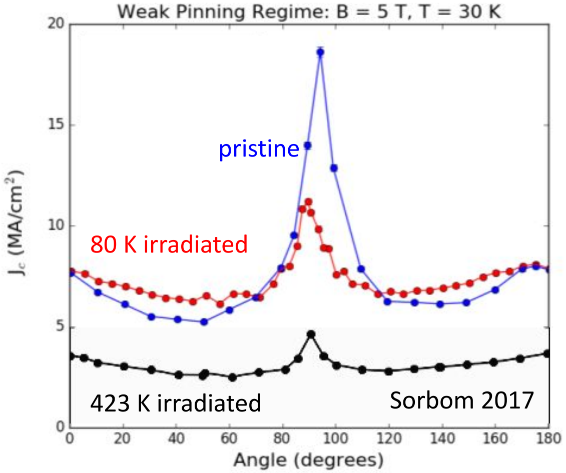
1.2 MeV proton irradiation



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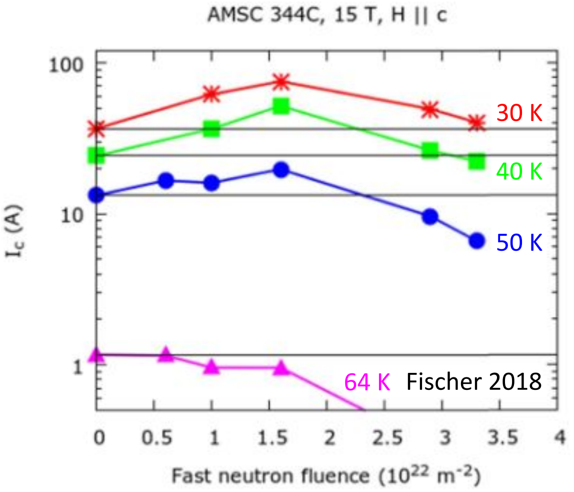

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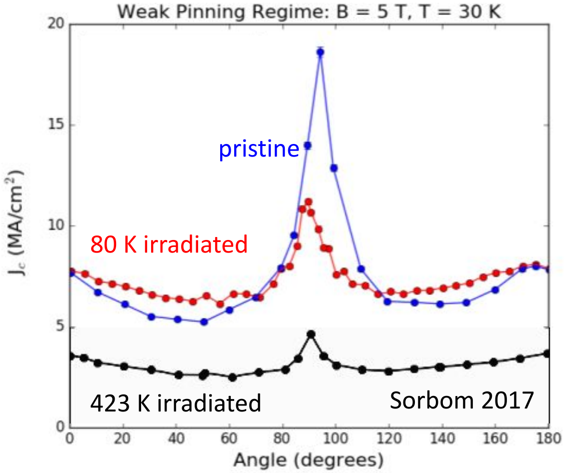
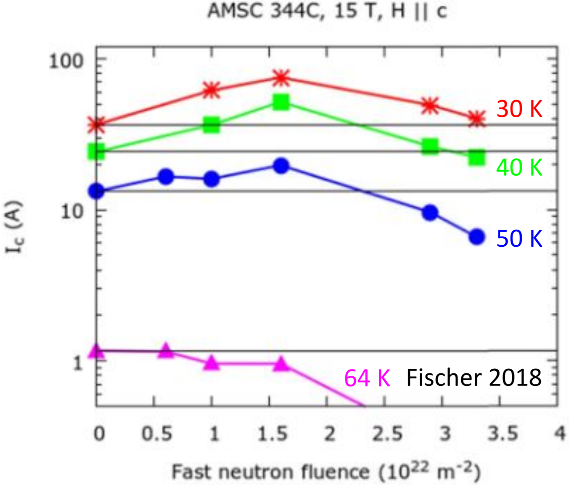


Severe knowledge gap about temperature effects!

# Previously missing: cold irradiation with in-situ analysis


Neutron irradiation at 330 K

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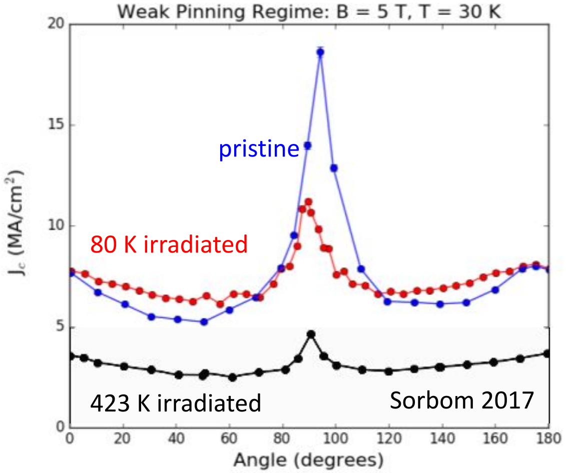
1.2 MeV proton irradiation

MIT developed an irradiation facility to explore the role of temperature for $I_c$ degradation, featuring:

- Irradiation at 20 K, the operation temperature of REBCO fusion magnets
- In-situ measurements to prevent annealing effects

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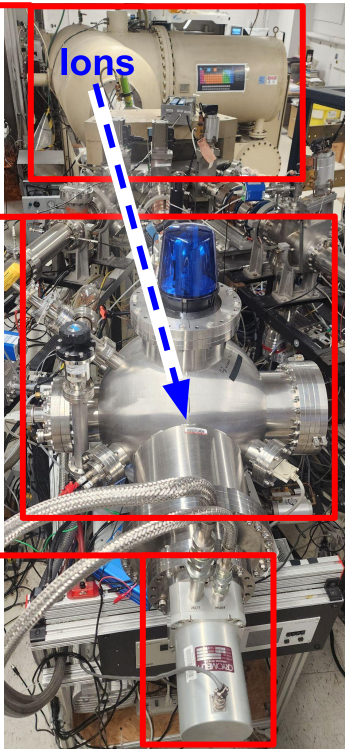
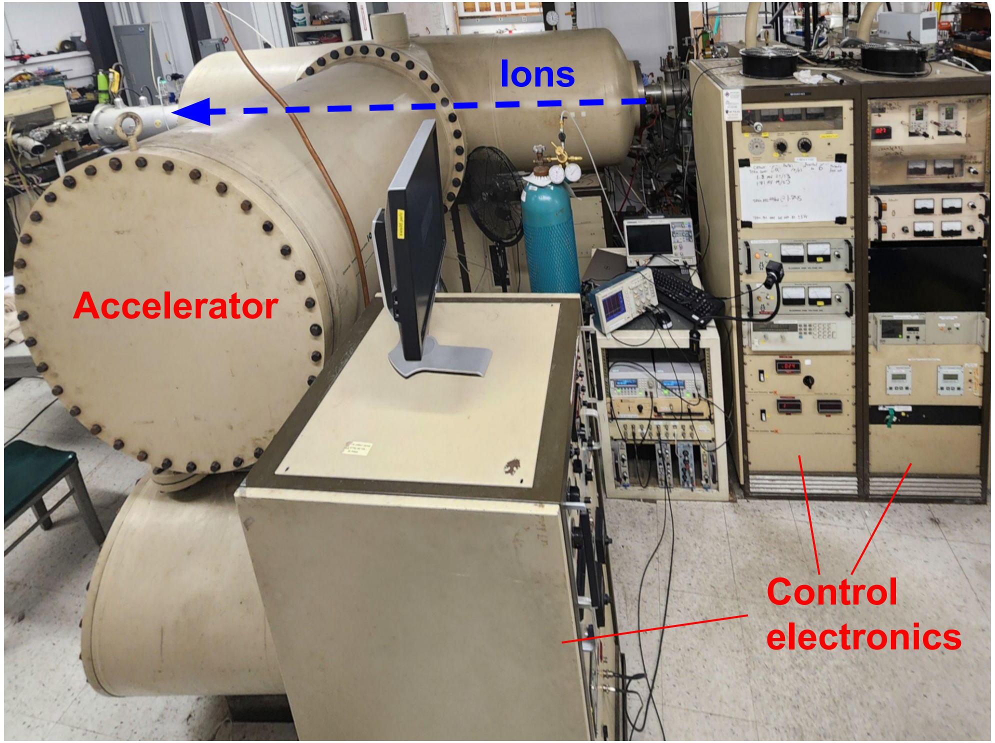
# MIT accelerator allows cold irradiation with various ions

**1.7 MV tandem accelerator**
- H, He, Li, O, Si, Au, etc
- Up to 100 µA beam curr.
- Up to 10.5 MeV

**Cryogenic irradiation chamber**
- 20-300 K temp. range
- Up to 100 A in-situ transport currents
- Measuring IV curves while irradiating

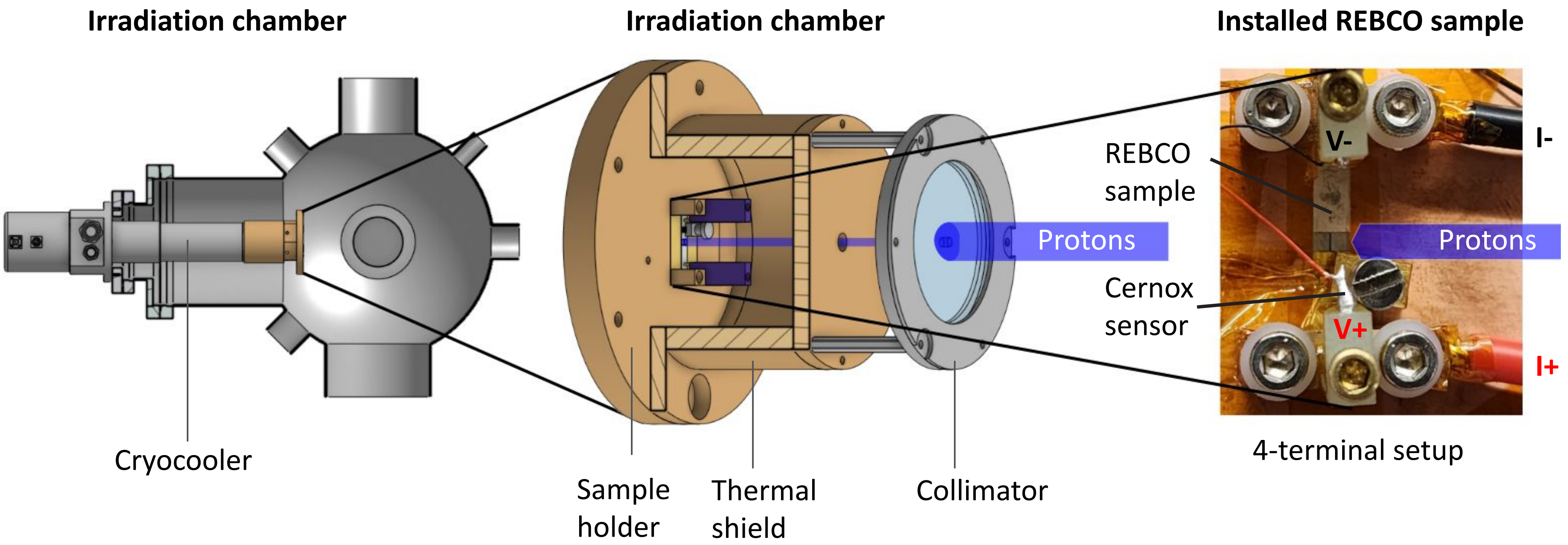
**Cryocooler**
- 25W @ 20 K
- 17 K base temperature





In-situ testing allows to preserve the radiation induced defect structure. Unique facility for 20 K ion irradiation and in-situ REBCO tape measurements - *Review of Scientific Instruments, 95(6):063907, 06 2024.*

# Custom irradiation setup enables in-situ measurements



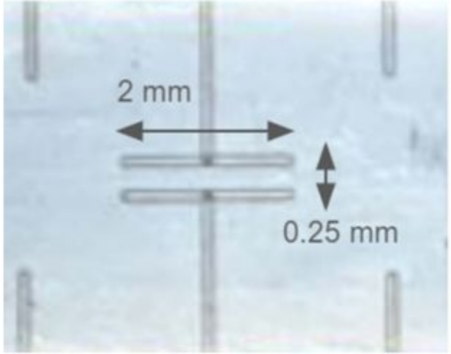
REBCO samples can be analyzed in-situ without warm-up which preserves the radiation induced defect structure. This resembles the temperature history of operating fusion magnets.

# Bridged samples reduce experimental challenges

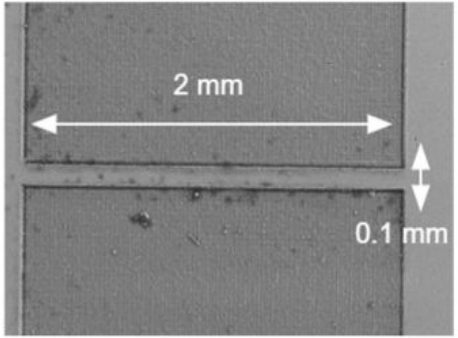
Advantages of using bridges

- Sample properties determined by bridge region
- Collimated beam (3 mm) covers entire bridge
  - no rastering needed
- Uniform proton flux density
- Required transport currents is kept to < 100 A
  - even at 20 K
- Negligible sample heating during measurements

AMSC sample design



Faraday Factory Japan sample design



# Standard experimental methods were used for irradiations, measurements and evaluations

- **1.2 MeV proton** irradiation at **20 K**, 77 K, 200 K and **300 K**
- Beam currents of typically **100 nA** through 8 mm$^2$ round collimator hole
- Beam current measurements using picoammeter
- **In-situ** 4-terminal transport current measurements
- Assessment of $\mathbf{I_c}$ and **n-value** at **20 K** and **77 K**:
  fitting linear line in log-log IV plot in range 0.2-20 µV and using $E_c$ = 1 µV/cm
- Assessment of $\mathbf{T_c}$:
  intersection of tangent to transition region and tangent of normal conducting region
- All data obtained in **self-field** conditions!

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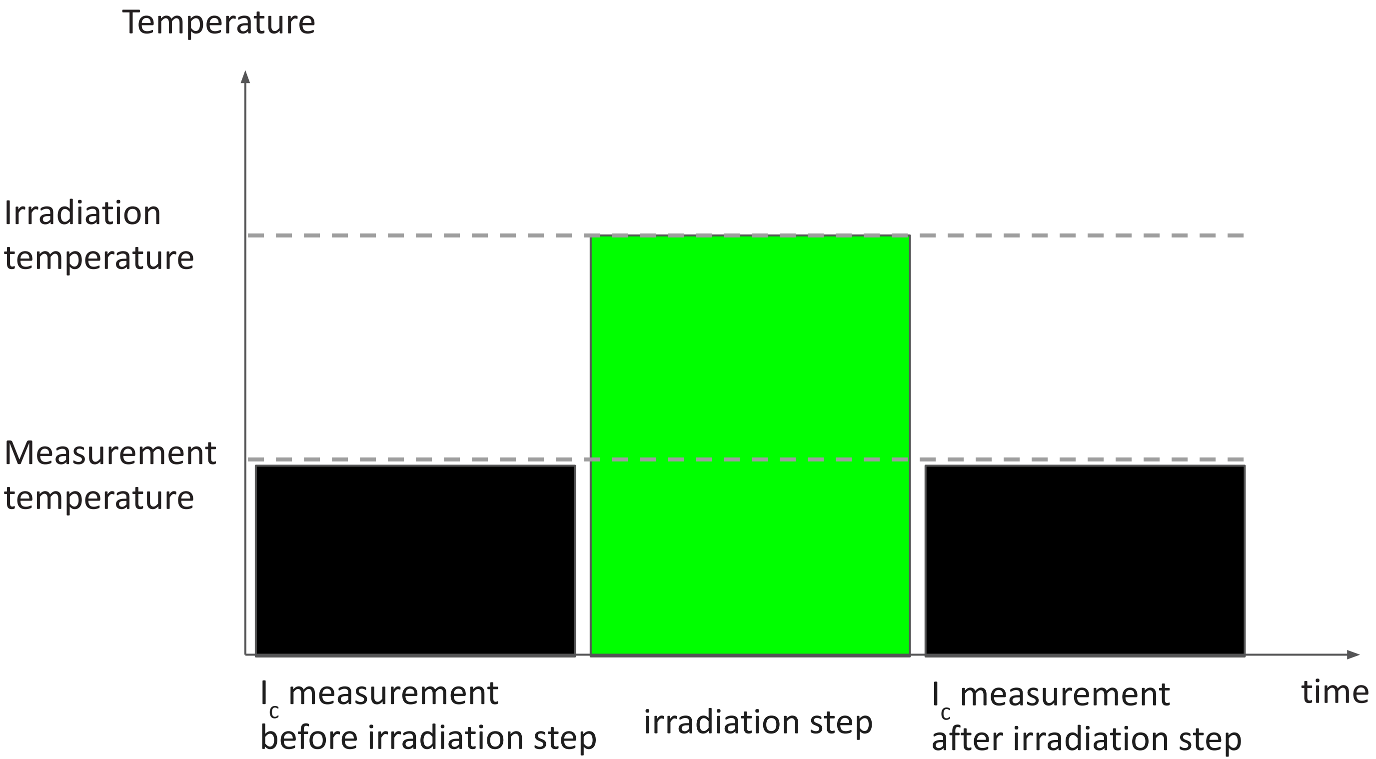
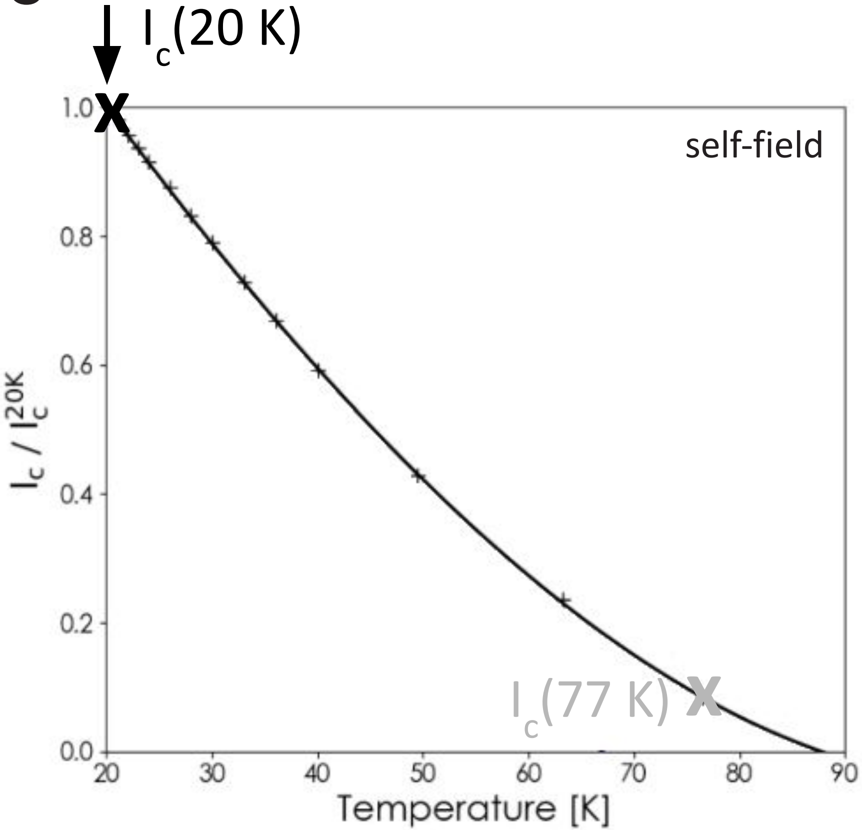
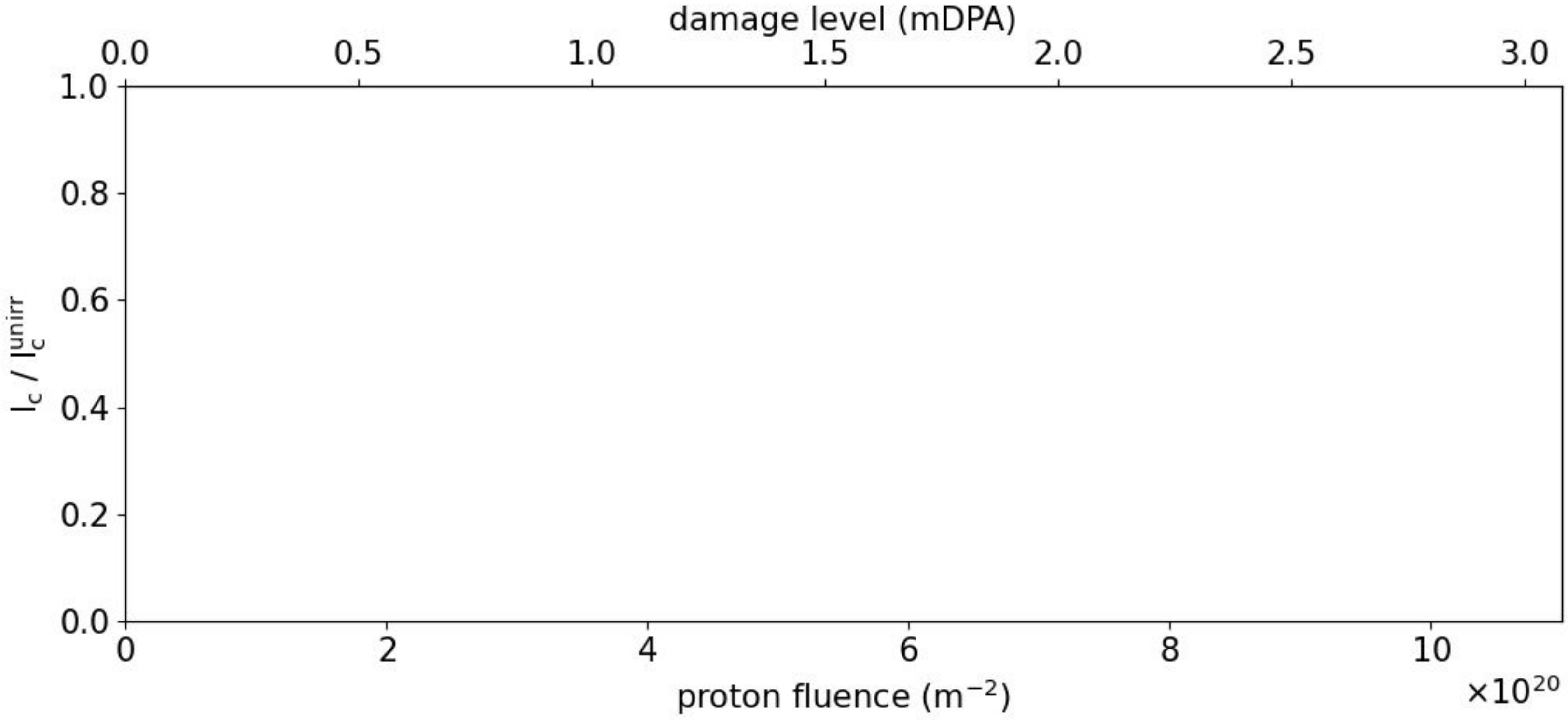
# Experimental procedure to assess radiation effects on $I_c$



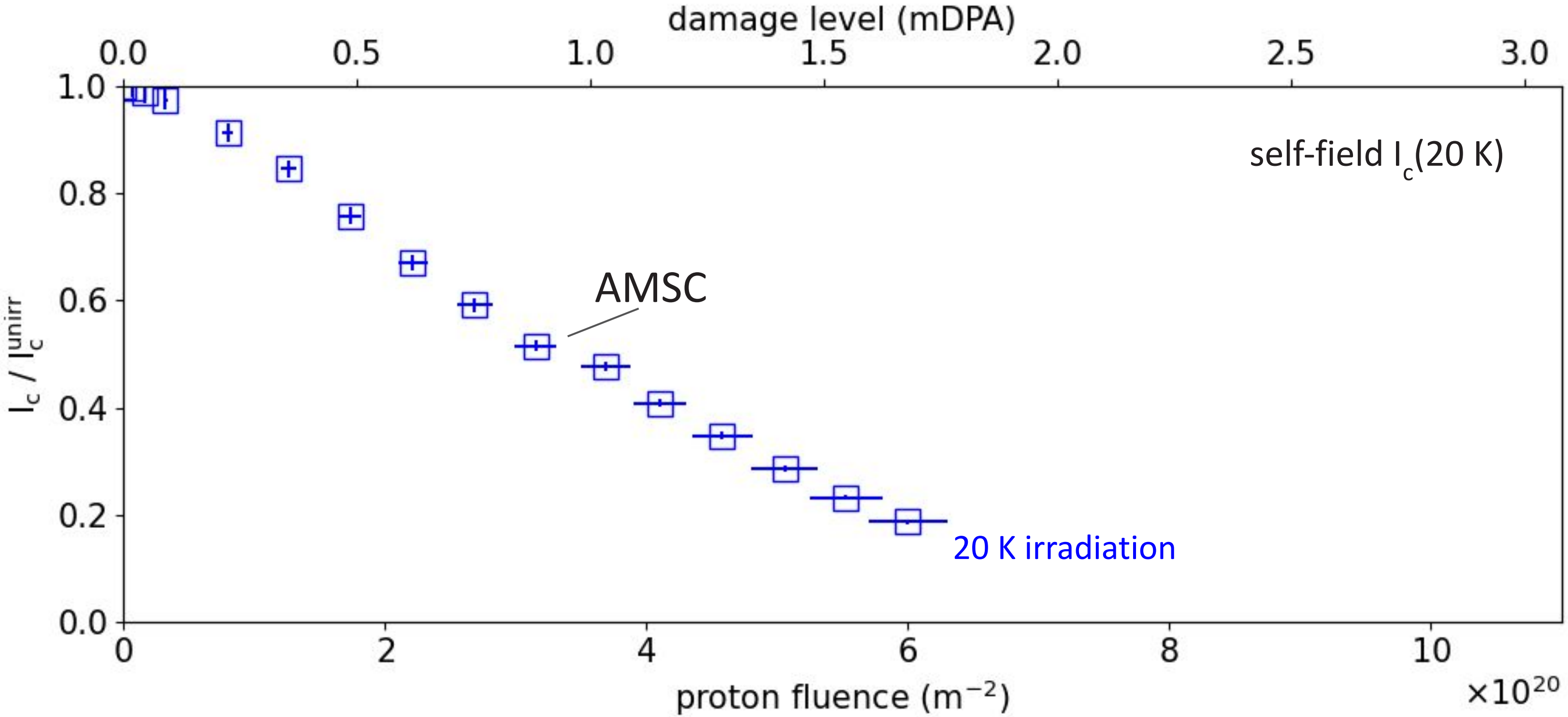
# Radiation effects on critical currents measured at low temperature



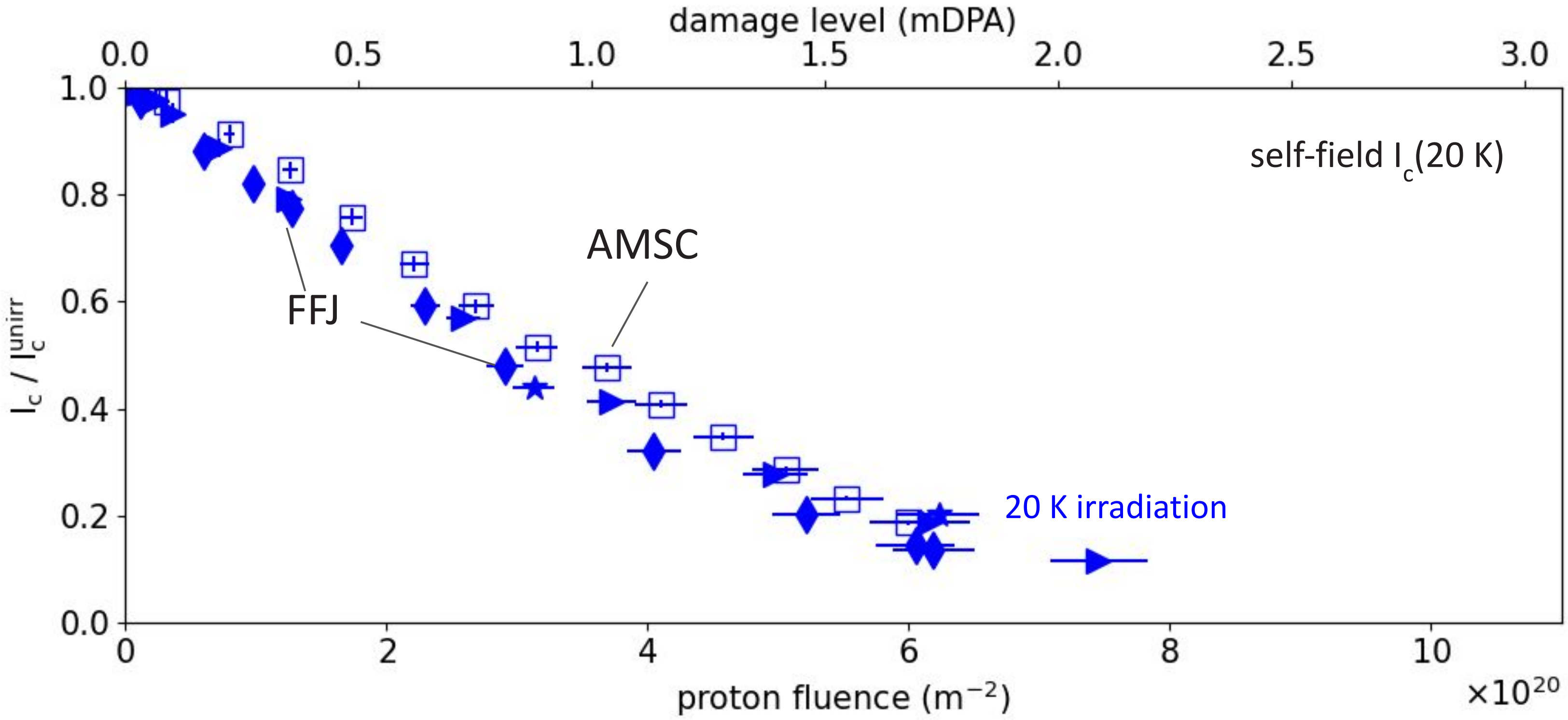
# How to understand the plots



# $I_c$ degradation after irradiation at 20 K

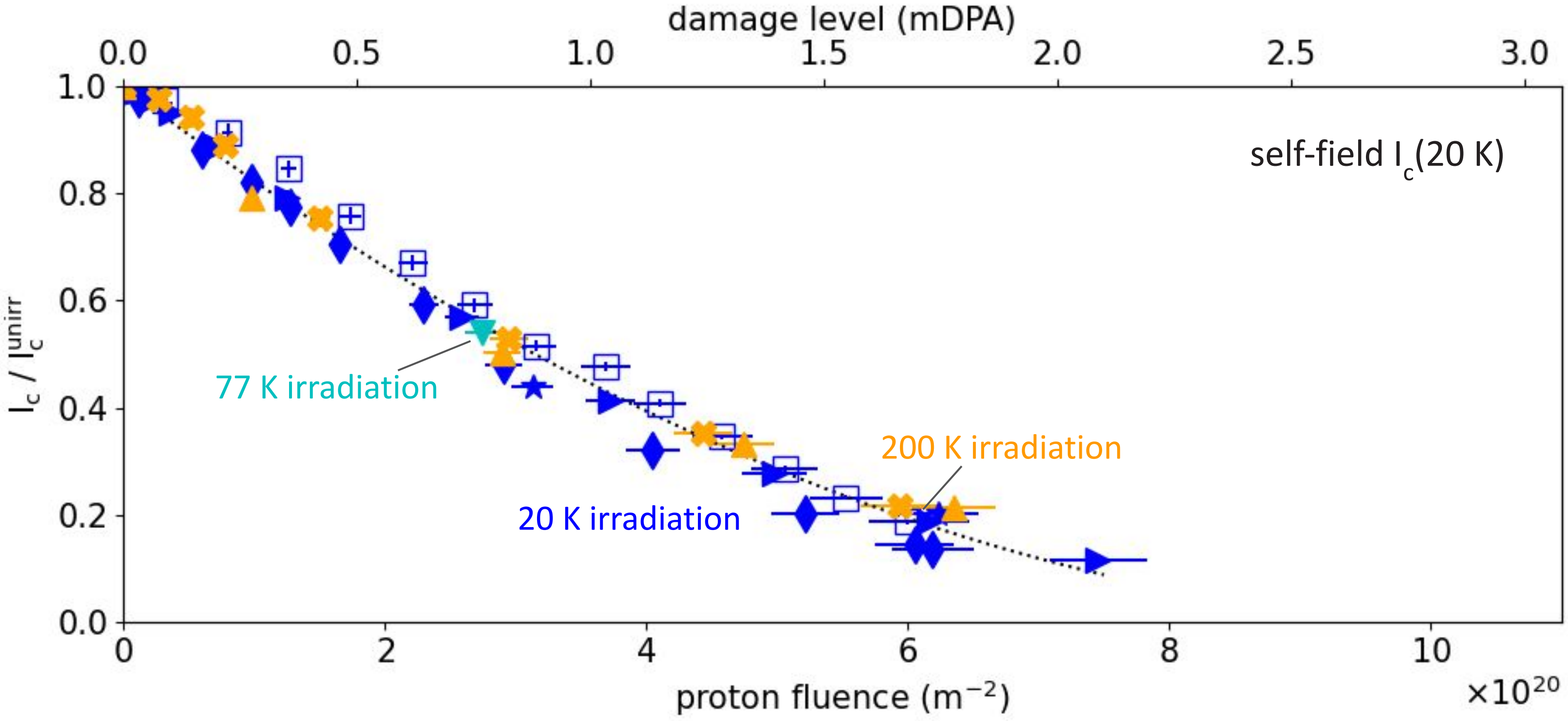


# Similar $I_c$ degradation after low temperature irradiation across different microstructures



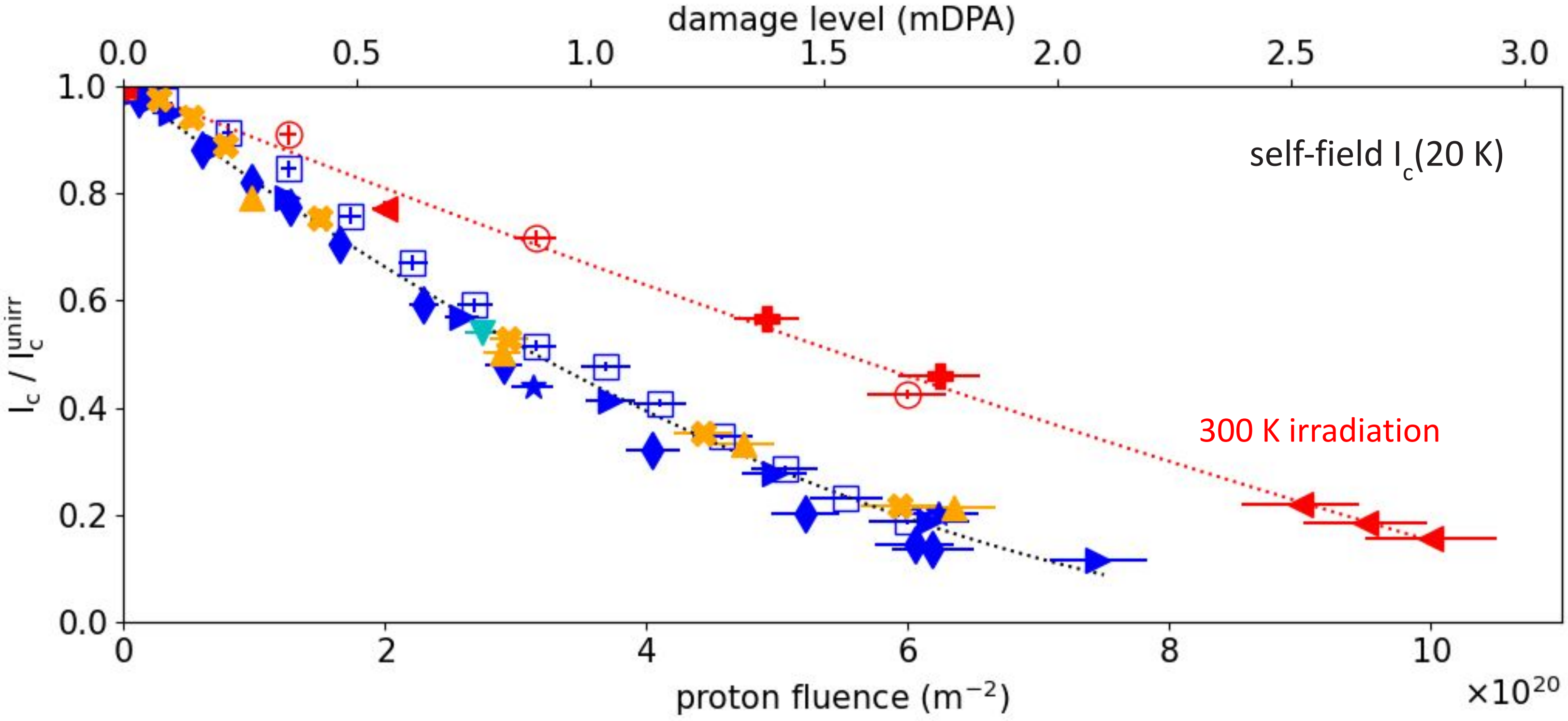
# Irradiations up to 200 K produce very similar $I_c$ degradation

MIT PSFC



# Warm irradiation is significantly less degrading

**MIT PSFC**



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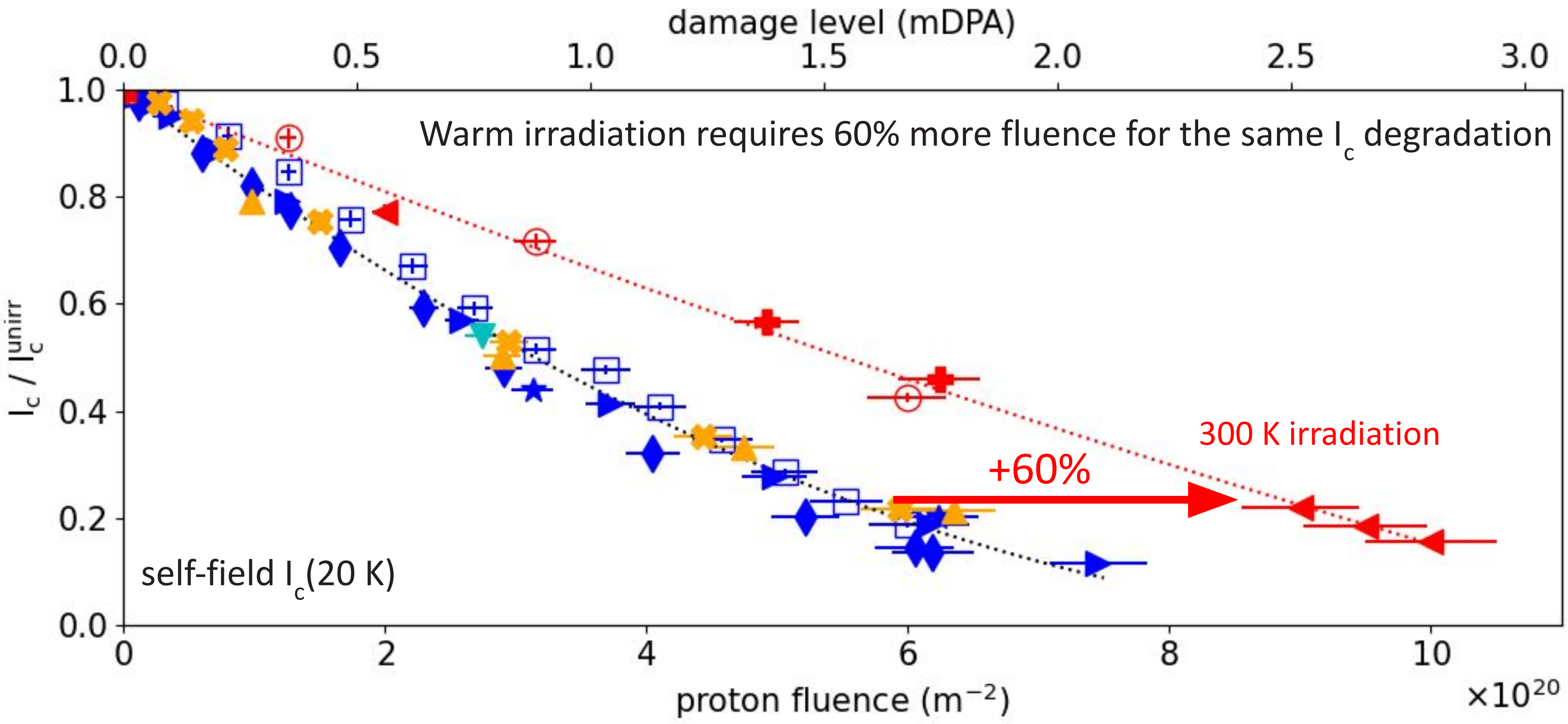

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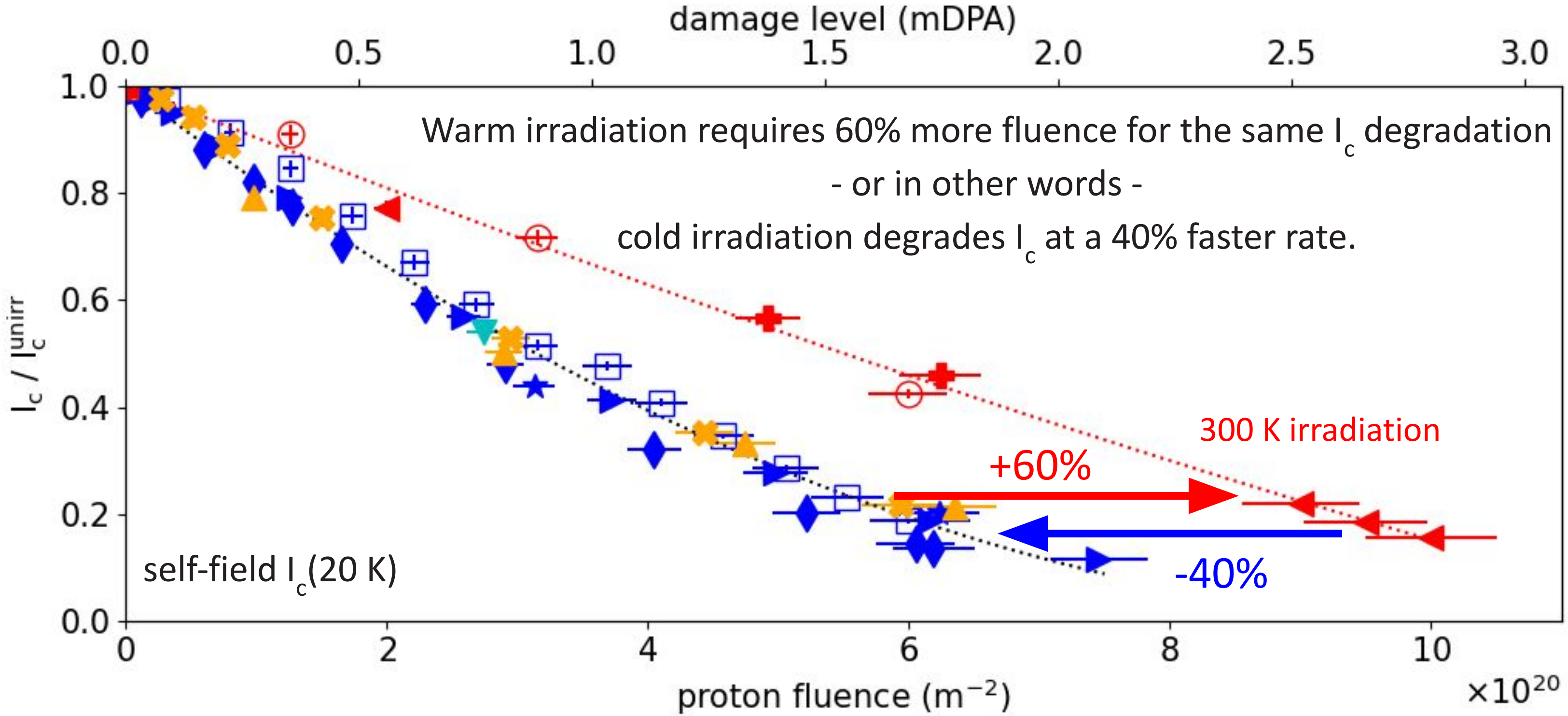


Warm irradiation requires 60% more fluence for the same $I_c$ degradation

- or in other words -

cold irradiation degrades $I_c$ at a 40% faster rate.

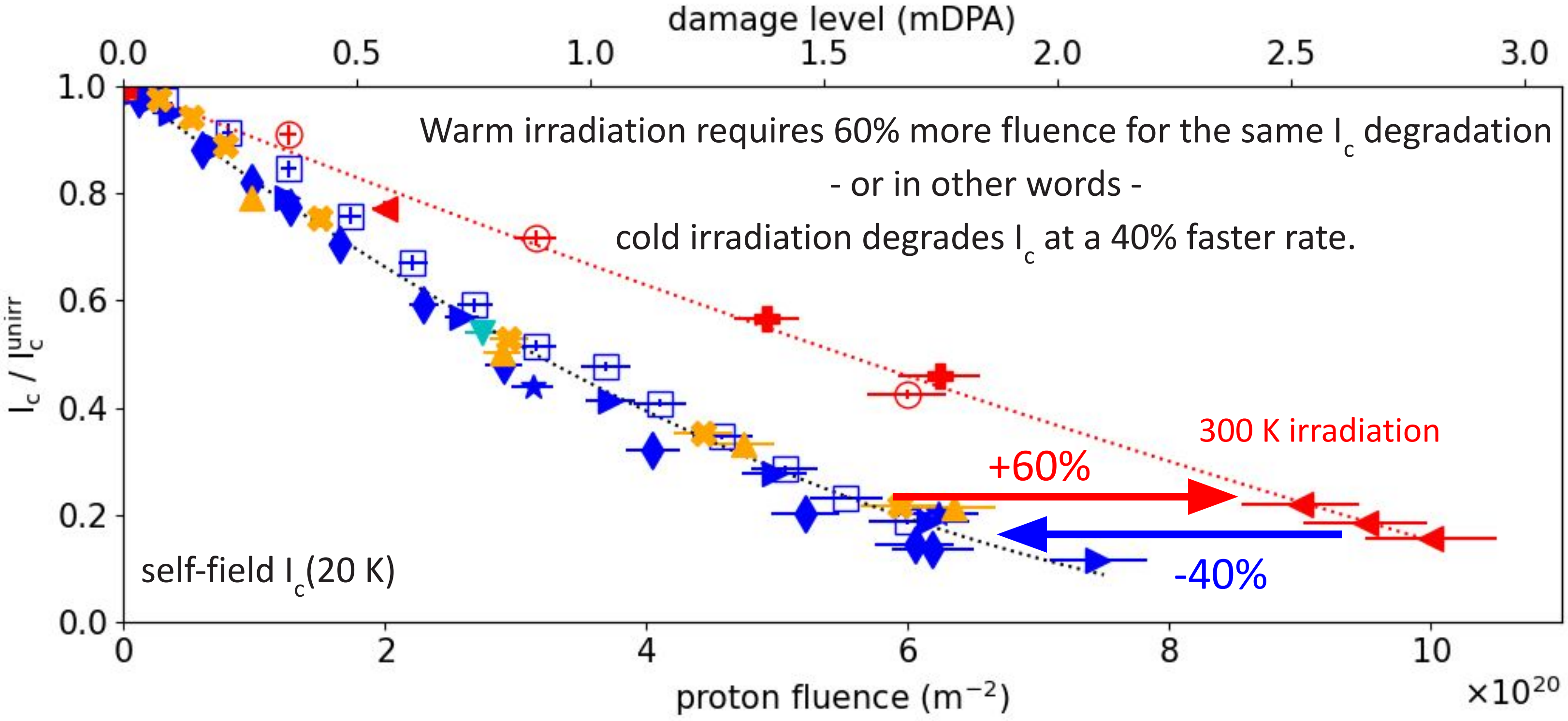
300 K irradiation

+60%

-40%

self-field $I_c$(20 K)

# Warm irradiation is significantly less degrading - due to inherent annealing which limits the accumulation of defects



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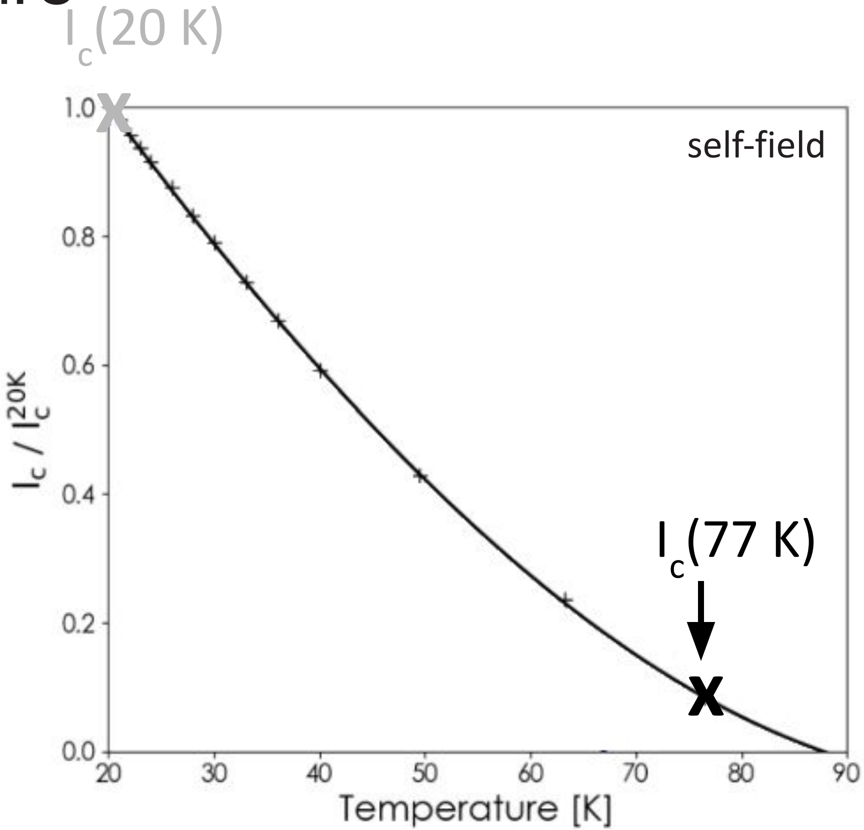
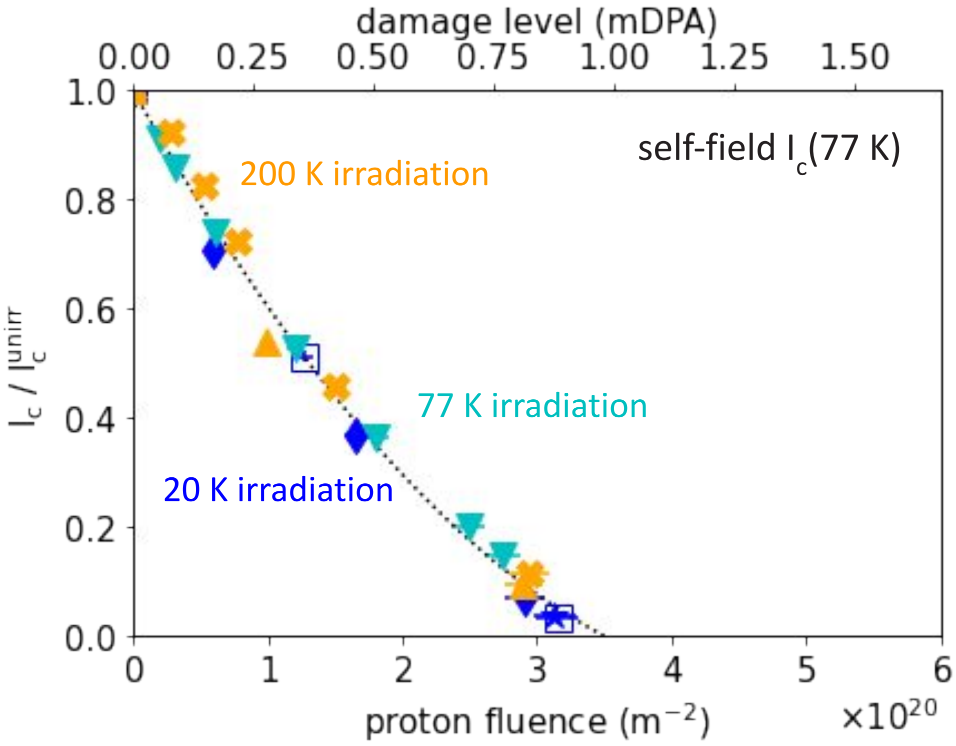
# Radiation effects on critical currents measured at high temperature

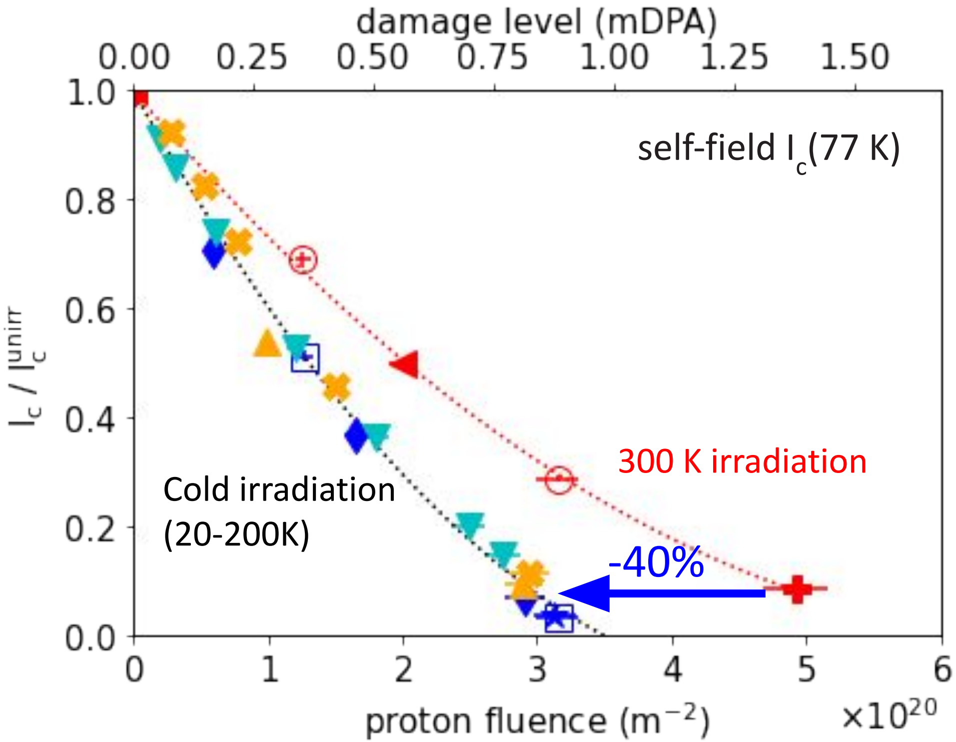


# Universal $I_c$(77 K) degradation for irradiations up to 200 K

MIT PSFC



# $I_c$(77 K) degrades in cold irradiations also at a 40% lower fluence compared to 300 K irradiations



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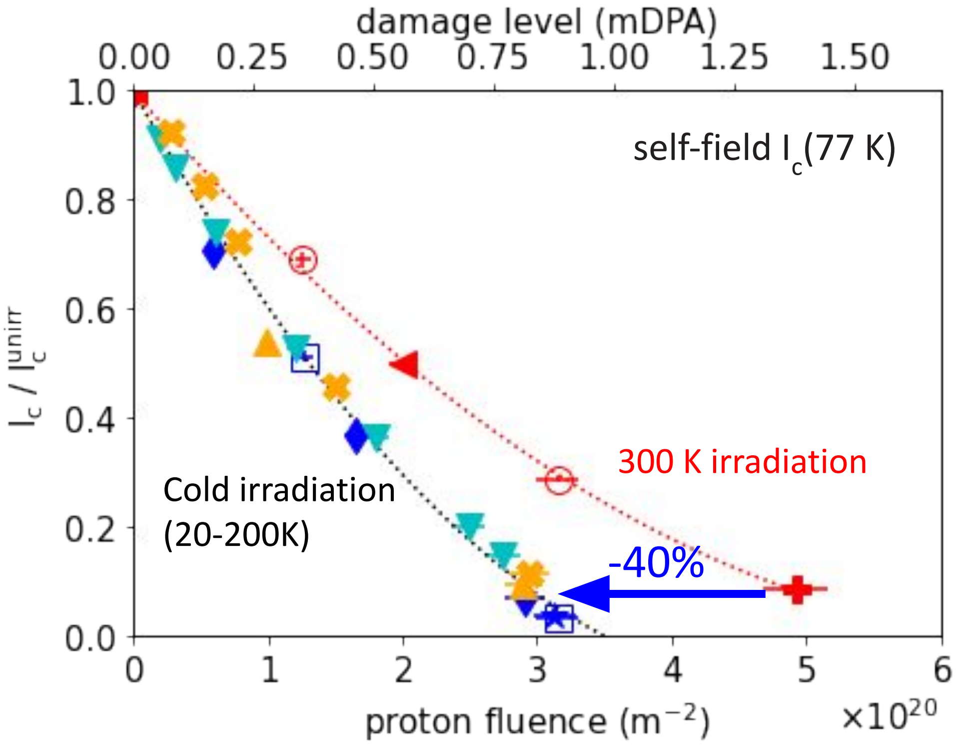

The critical currents $I_c$(T) might generally degrade in cryogenic irradiations (20-200 K) at a ~40% lower fluence compared to warm (300 K) irradiations, independent of measurement temperature T (20-77K).

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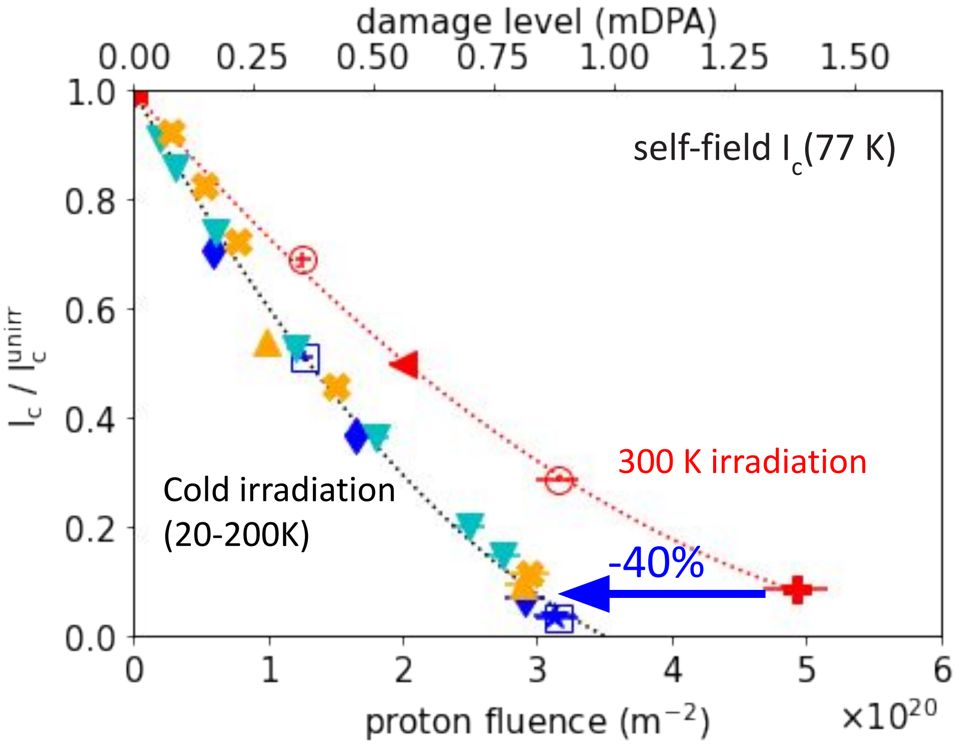
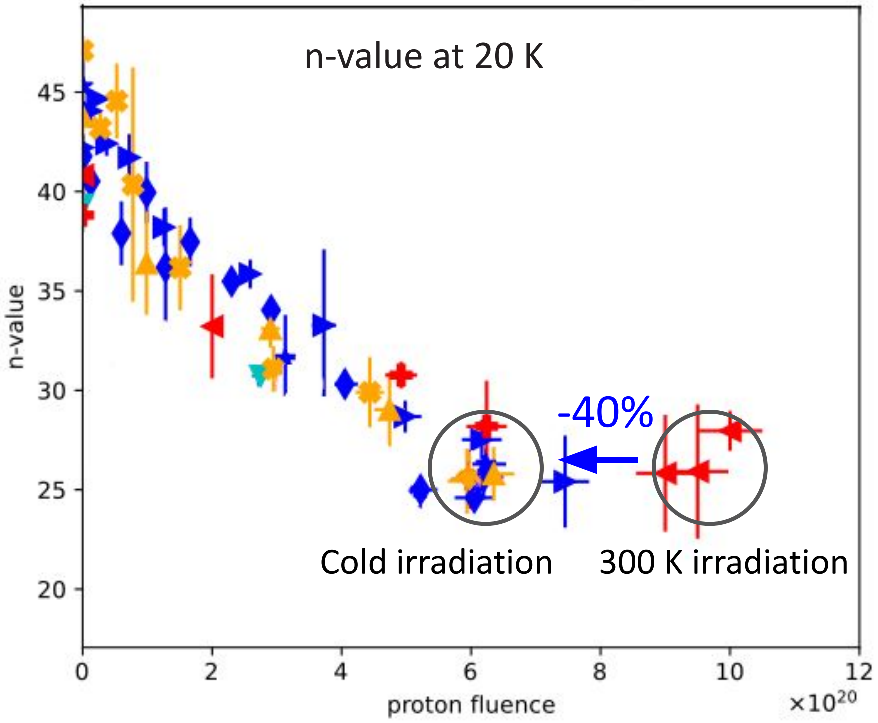


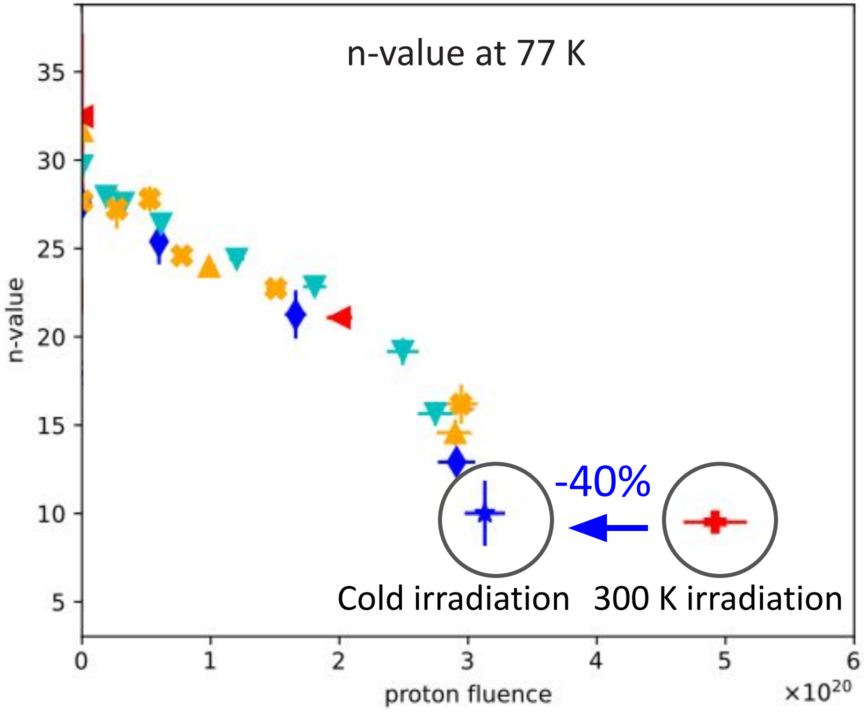
The critical currents $I_c$(T) might generally degrade in cryogenic irradiations (20-200 K) at a ~40% lower fluence compared to warm (300 K) irradiations, independent of measurement temperature T (20-77K).

How does this translate to in-field behavior?
Will fusion magnets 40% faster than previously assumed?
At a fast neutron fluence of $<2x10^{22}m^{-2}$ instead of $3x10^{22}m^{-2}$???

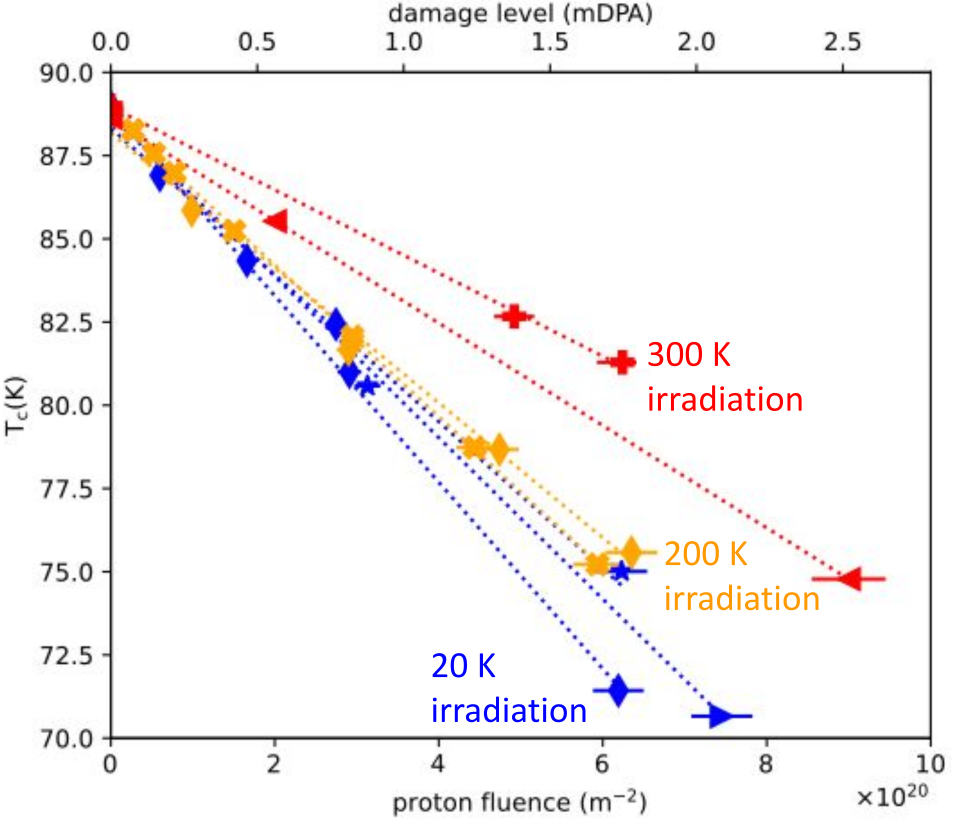
MIT PSFC

# The n-values also degrade at ~40% lower fluences in cold irradiations





# Faster decrease of $T_c$ in cold irradiations indicates build-up of higher point defect concentration



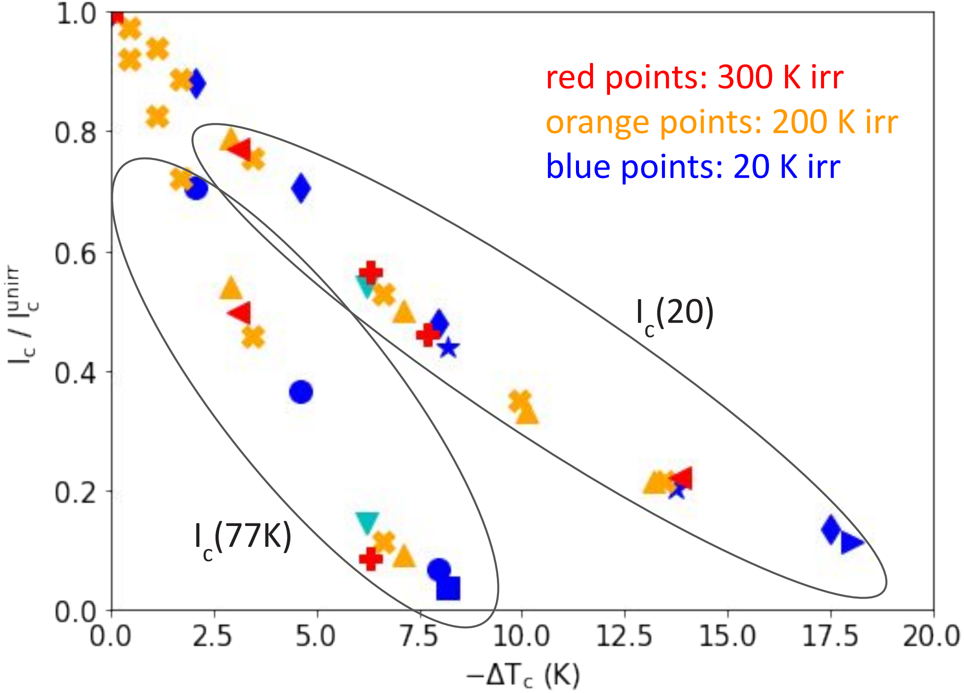
Average $T_c$ degradation per proton fluence of $10^{20}$ $m^{-2}$ for different irradiation temperatures:

300 K irr: -1.42 K

200 K irr: -2.21 K

20 K irr: -2.51 K

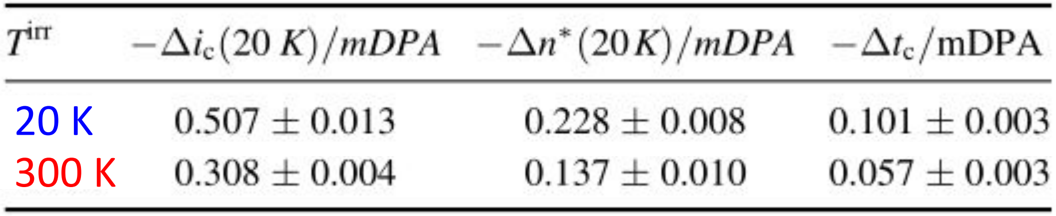
# The same $T_c$ degradation corresponds to the same $I_c$ degradation - independent of irradiation temperature!



This suggests that $T_c$ reduction is a good metric for radiation damage!

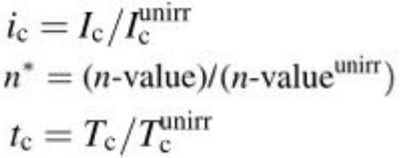
# Why does the irradiation temperature affects all superconducting parameters in a very similar way?

Degradation of superconducting properties per mDPA



| $T^{\mathrm{irr}}$ | $-\Delta i_c(20\,K)/mDPA$ | $-\Delta n^*(20\,K)/mDPA$ | $-\Delta t_c/\mathrm{mDPA}$ |
|---|---|---|---|
| 20 K | $0.507 \pm 0.013$ | $0.228 \pm 0.008$ | $0.101 \pm 0.003$ |
| 300 K | $0.308 \pm 0.004$ | $0.137 \pm 0.010$ | $0.057 \pm 0.003$ |
| | -39% | -40% | -44% |

Reduced parameters



$$i_c = I_c/I_c^{\mathrm{unirr}}$$
$$n^* = (n\text{-value})/(n\text{-value}^{\mathrm{unirr}})$$
$$t_c = T_c/T_c^{\mathrm{unirr}}$$

All investigated superconducting parameters ($I_c$, n-value and $T_c$) degrade at ~40% lower fluences in irradiations at 20 K compared to irradiations at 300 K. This observed universality could hint at a common underlying origin of the degradation - a reduction of the superfluid density?

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# How to calculate the superfluid density

## Dependence of ρ(0 K) on $T_c$

$$\rho \propto \frac{t_c}{1+k(1-t_c)}$$

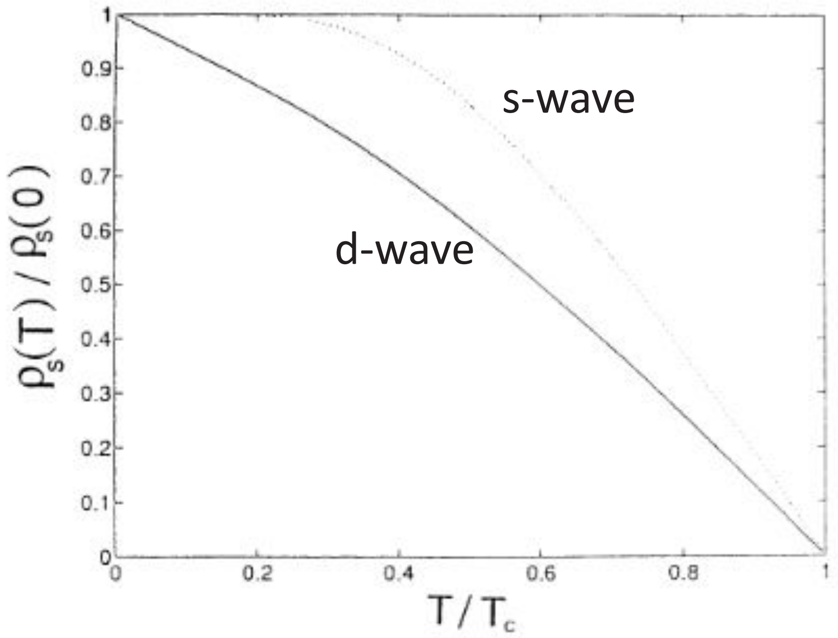
$\mathrm{k} = 16.5$ for REBCO

$t_c = T_c/T_c^{\mathrm{unirr}}$

Michael Eisterer (TU Wien) suggests a decrease of the superfluid density ρ(0 K) according to Homes' law, ICSM 2024, Turkey

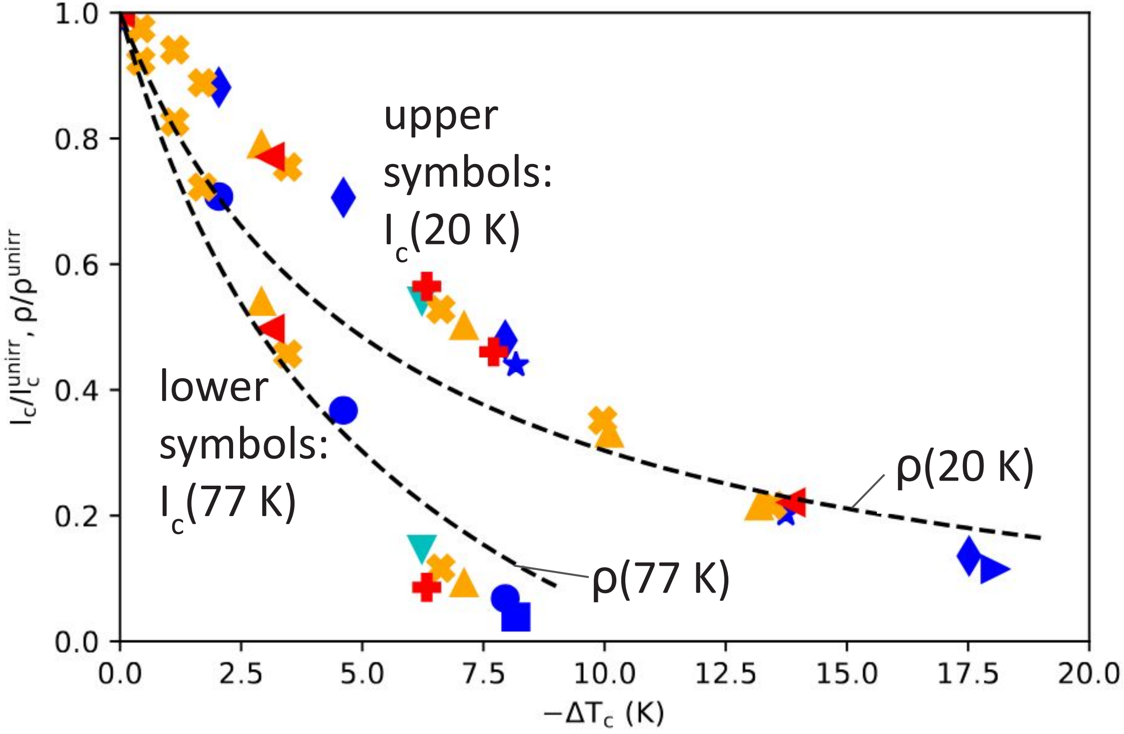
These two inputs allow calculating the superfluid density ρ(20 K) and ρ(77 K) in our REBCO samples for different $T_c$ reductions.

## ρ(T) for d-wave superconductors



Won H and Maki K 1994 *d*-wave superconductor as a model of high-$T_c$ superconductors *Phys. Rev.* B **49** 1397–402

# Superfluid density and critical currents correlate



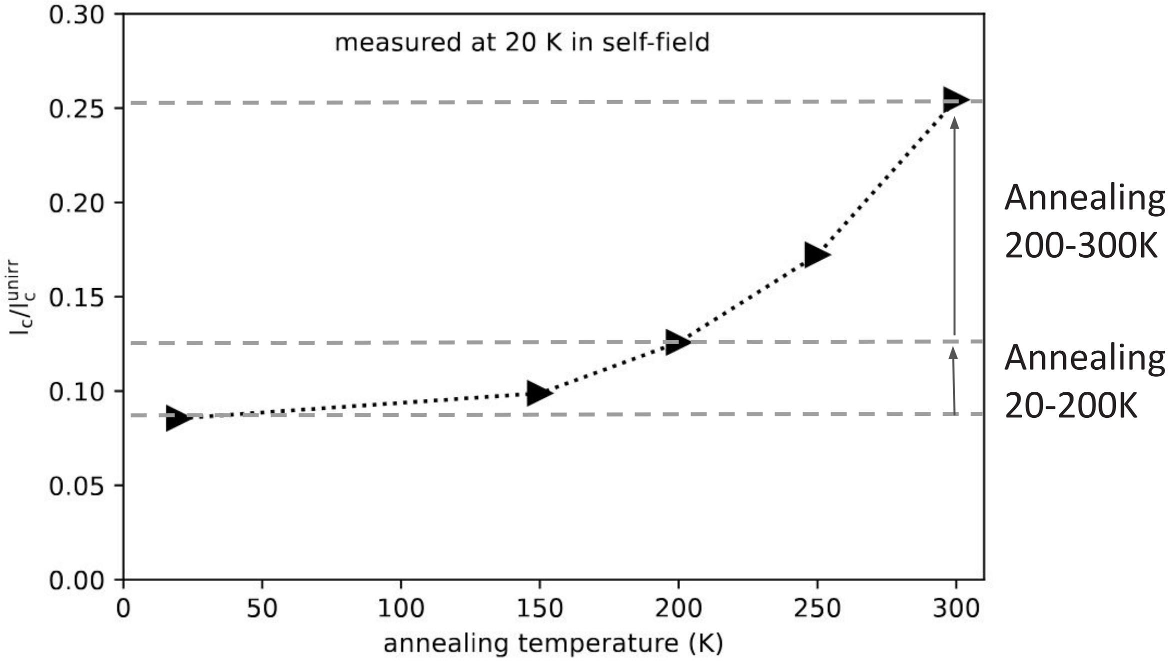
The calculated superfluid density has a similar functional dependence on $T_c$ degradation as the critical currents.

A model that bases the degradation of $I_c$ on a reduction of ρ(T) seems to be compatible with our experimental data

# Outline of presentation

- Motivation for this research
- Replication of fusion environment
- Cryogenic ion irradiation facility at MIT
- Experimental results
  - Cryogenic vs warm irradiation
  - Degradation mechanism
  - Annealing
- Next steps
- Conclusions

# The annealing recovery accelerates with temperature

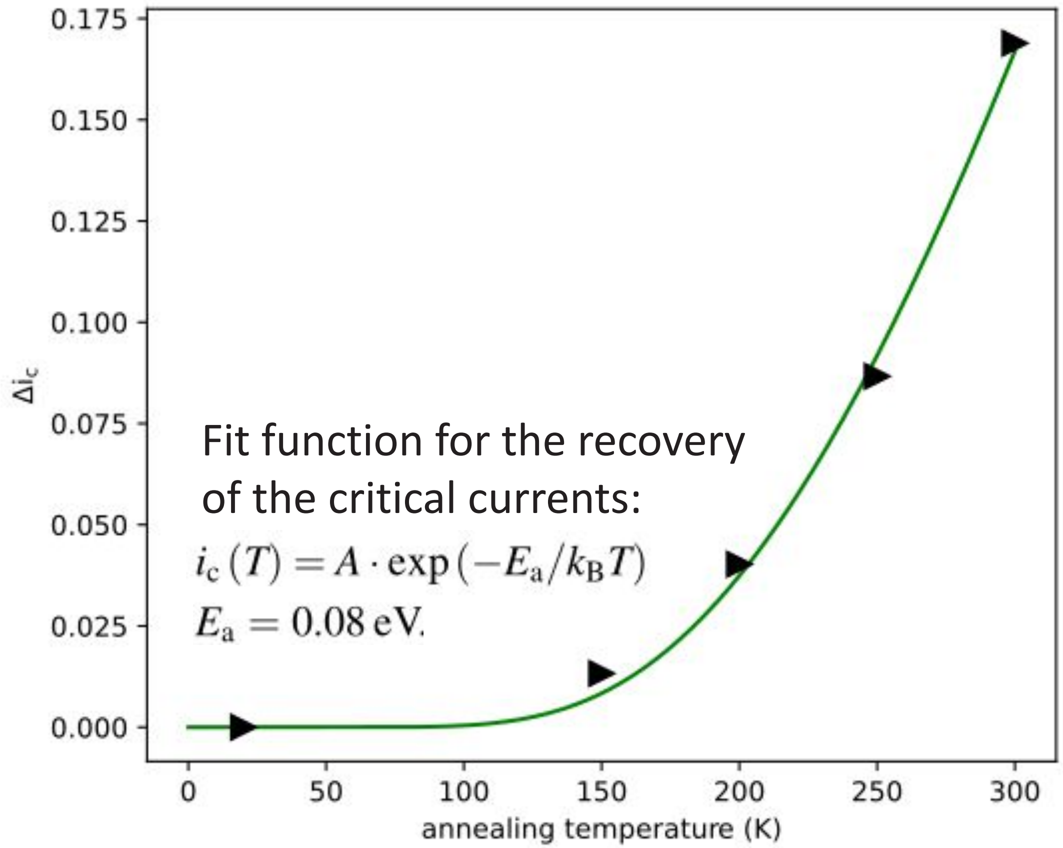


Annealing 200-300K

Annealing 20-200K

The recovery of the critical current is relatively small up to 200 K, but increases significantly at higher temperatures, indicating substantial reconfiguration of the radiation induced defect structure

# Does the fit parameter $E_a$ have a physical meaning?



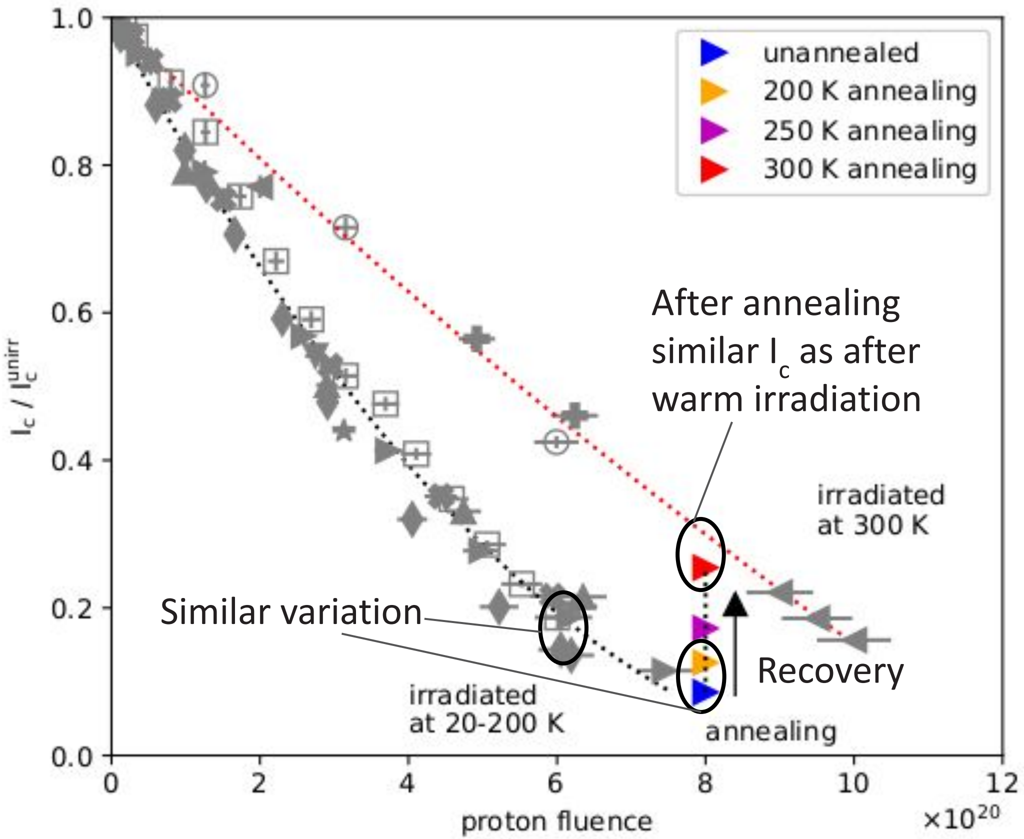
Fit function for the recovery of the critical currents:

$$i_c(T) = A \cdot \exp(-E_a/k_B T)$$

$$E_a = 0.08\,\text{eV}.$$

Typical reported migration energies are around 1 eV.

# Cold irradiation + annealing = warm irradiation?



After annealing similar $I_c$ as after warm irradiation

Similar variation

Recovery

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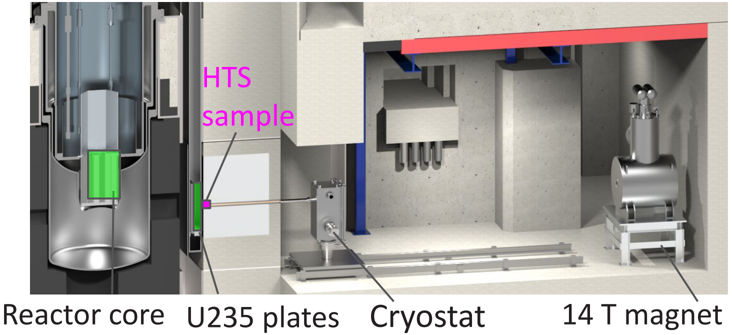
# What comes next?

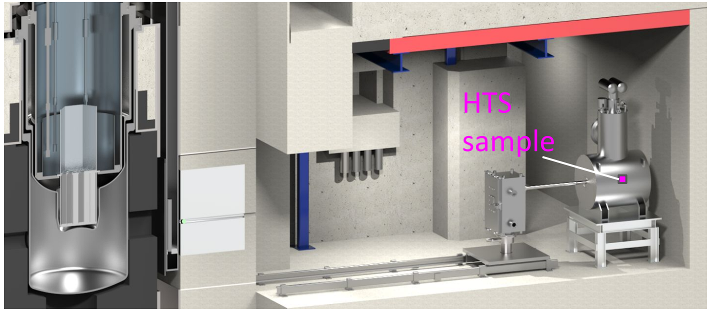
- Test the $I_c$ degradation model of Michael Eisterer against our cryogenic proton irradiation results
- Detailed experiments on how annealing temperature and duration influence recovery
- Upgrade ion irradiation setup with magnetic background field (~5 T)
- 2025: commissioning facility for cryogenic neutron irradiation and in-situ testing
  - Fast neutron fluences of >$5x10^{22}$ $m^{-2}$
  - Preservation of radiation induced defect structure
  - $I_c$ measurements in fields up of to 14 T
  - Resolving angular dependent $I_c$ degradation

# Cryogenic neutron irradiation facility will provide the most fusion-like test environment for REBCO tapes

### Irradiation configuration



### Measurement configuration

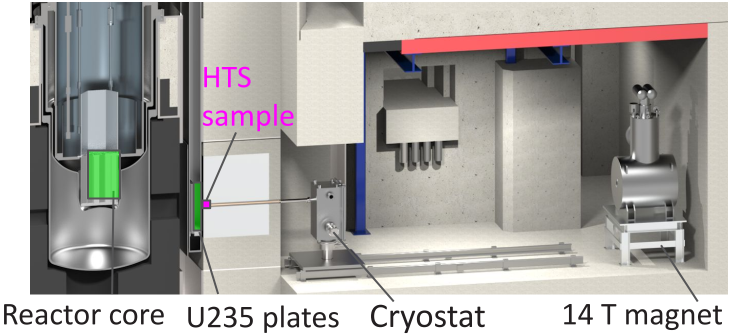


### Features and capabilities of cold neutron irradiation facility

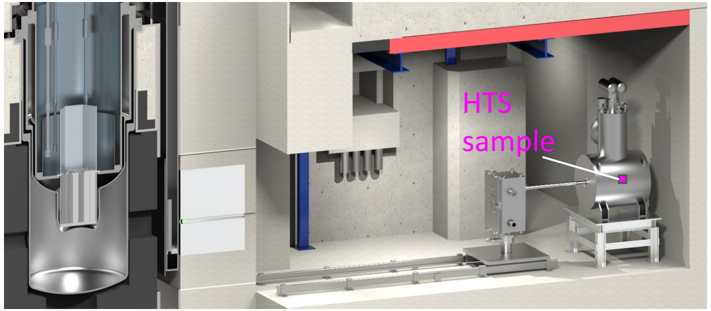
- Fast neutron fluence of $5\text{x}10^{18}$ $\text{cm}^{-2}$ within ~ 2 months
- Similar neutron spectrum as at fusion magnet position
- Temperature range 20-300 K
- High magnetic background field (14 T)
- Insitu transport current measurements up to 100 A
- $I_c$ (T,B,θ) measurements of REBCO tapes
- Testing radiation response of other fusion magnets parts
    - Sensors
    - Fibre optics
    - Insulators
    - Stabilizers (copper, solder)

# Cryogenic neutron irradiation facility will provide the most fusion-like test environment for REBCO tapes

**Irradiation configuration**



**Measurement configuration**



**Checklist for fusion-like conditions**

| | |
|---|---|
| ☺ | irradiation temperature |
| ☺ | annealing effects prevented |
| ☺ | high magnetic background field |
| ☺ | irradiation type |
| ☺ | $I_c$ anisotropy assessment |
| ☺ | transport current measurements |

Facility becomes available this year!

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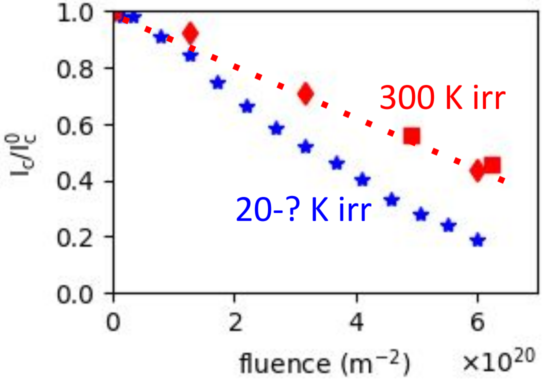
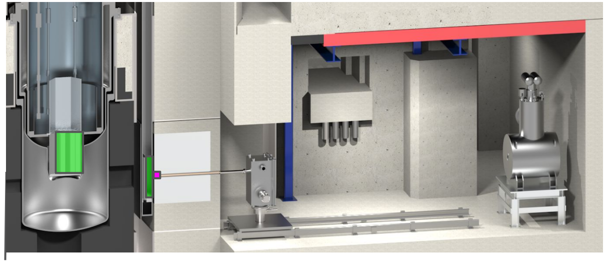
# Conclusions

- The critical current degradation seems almost independent of irradiation temperature - as long as it is low enough! TBD:
  - How does the microstructure change between 200-300 K?
  - Is there physics behind the fit parameter $E_a \approx 0.1$ eV?
- Fusion magnets might degrade at significantly lower fluences than previous results obtained in warm irradiations suggest!
- Our experimental data is compatible with a degradation model based on the reduction of the superfluid density
- Critical next step is to study the degradation of $I_c(T, B, \theta)$ after cryogenic neutron irradiation with fusion relevant spectrum to relevant fluences in-situ with transport currents! Results are essential to build optimized fusion magnets!
- We warmly invite collaborations to utilize our facilities!





Operational this year!